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Criterion of Alternative Initiation of Cold Cracking in HAZ or Weld Metal for Root Pass Welds of High Strength Steels†

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Abstract

In this study, in order to reveal the criterion under which cold cracking in root pass welding occurs alternatively in HAZ or weld metal, the effects of applied stress, diffusible hydrogen content, hardnesses of HAZ and weld metal on the crack initiation site were studied utilizing the TRC test for HT60, HT80, HY130 and 2¼ Cr-1Mo steels. Then, "Critical stress vs. time diagram" which represent the change in the critical stress in weld metal and HAZ vs. time lapse was proposed as the criterion considering the distribution of diffusible hydrogen in weld zone.

Consequently, all the tendencies of crack initiation in root pass welding can be well explained by combining the progress of applied stress and "Critical stress vs. time diagram".

KEY WORDS: (Cold Cracking) (High Strength) (HAZ) (Weld Metal)

1. Introduction

It has been well known[1)-6)] that hydrogen-induced cold cracking in root pass welding in usual weldable high strength steels generally occurs in the heat-affected zone (HAZ). Therefore, almost all the reports published hitherto have dealt with the prevention of cold cracking in HAZ on the basis of effects of initial diffusible hydrogen content, residual diffusible hydrogen content at 100°C, maximum hardness, concept of P_{cm}, restraint intensity, restraint stress and so on. Consequently, welding researchers can predict to some extent the crack initiation or the crack free in HAZ in welding fabrication.

However, recently, HY type steels have been gradually utilized to be accommodated to more serious environment because of their high yield ratio and high toughness. Among them, however, cold cracking predominantly occurs in weld metal in the root pass welding of HY130[2)-4)], so the tendency of crack initiation in weld metal must be investigated for such material. Thus now the criterion by which the alternative crack initiation in HAZ or weld metal can be predicted in the welding of such type of steels must be established for the prevention of cold cracking.

As regards this problem, there have been few suggestive reports[5)-9)] until now, from which it may be understood that hardnesses of HAZ and weld metal, diffusible hydrogen content and degree of restraint are the major factors affecting the alternative crack initiation in HAZ or weld metal. Roughly describing, higher hardness of weld metal than HAZ, high diffusible hydrogen content or high restraint tends to cause the cracking in the weld metal. However, no researcher has been able to give any concept of the individual and mutual effects of these factors.

Therefore, this study has been planned to systematically reveal the individual, and mutual effects of these factors on the alternative crack initiation in HAZ or weld metal. In this study, the TRC test has been used to clarify the loading temperature and stress level, and fractographic technique has been utilized to identify precisely the crack initiation site. Then, the qualitative criterion for alternative crack initiation in HAZ or weld metal has been proposed which enable us to explain well all the experimental results.

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2. Materials Used and Experimental Procedures

2.1 Materials used

Base metals used were weldable heat-treated high strength steels HT60, HT80 and HY130 whose nominal ultimate strengths were 60, 80 and 100 kgf/mm^2, respectively and 2¼Cr-1Mo steel corresponding to ASTM alloy A387-Gr. 22. Covered electrodes used were D5016, D5816, DT2416, D8016*) and E(130)M**) which well matched HT60, 2¼Cr-1Mo, HT80 and HY130 in strength levels, respectively. Designations, type of chemical compositions, yield and ultimate tensile strengths of materials used were shown in **Table 1**.

Table 1 Designation, type of chemical compositions, yield and tensile strengths of materials used

	Material	Type of composition	Yield strength (kgf/mm^2)*	Ultimate strength (kgf/mm^2)*	Thickness (mm)
Base metal	HT60 (SM58Q)	0.07Mo-V	56	66	31
	HT80	0.7Cr-0.4Mo-V	81	85	32
	SCMV-4	2$^1/_4$Cr-1Mo	64	85	35
	HY130	5.2Ni-Cr-Mo-V	94	102	35
Electrode (4mm dia.)	D5016	-	50	58	-
	D5816	0.5Ni-0.2Mo	57	66	-
	D8016	2.6Ni-Cr-Mo	74	85	-
	DT2416	2$^1/_4$Cr-1Mo	-	-	-
	E(130)M	2.7Ni-Cr-Mo	95	100	-

* The data for electrodes were measured from all deposited metal

2.2 TRC tests used

2.2.1 *Ordinary TRC test*

The TRC test was done for various combination of base metals and electrodes under the condition of various applied stress and diffusible hydrogen content in order to reveal the cracking mode which was related with the alternative crack initiation in HAZ or weld metal. The setting up of the TRC test specimen was shown in **Fig. 1**, in which the weld bead was laid in the y-groove with root gap of 2 mm by SMA welding. The welding conditions used were welding current of 170A, arc voltage of 25V, welding speed of 150 mm/min and no preheating. The applied stress ranging from 40 to 100 kgf/mm^2 was loaded mainly at 150°C on cooling after welding except for the case where the stress was loaded at 300°C or 20°C in order to study the effect of loading temperature on the cracking mode. Diffusible hydrogen content was varied by changing the baking temperature of electrode and using wetting electrode. **Table 2** summarizes the diffusible hydrogen content measured with gas-chromatographic method. **Table 3** summarizes the maximum hardness of HAZ and average hardness of weld metal in the various combinations of base metal and electrode. The hardness of HAZ ranges from 360 to 410 and that of weld metal does from 240 to 385. The reason why the range of the hardness of HAZ was not so wide was that the recent weldable high strength steels in Japan contained relatively low carbon which has the strongest effect on the maximum hardness of HAZ. Consequently, it is considered that the crack susceptibility of HAZ was not so widely changed as that of weld metal in this study.

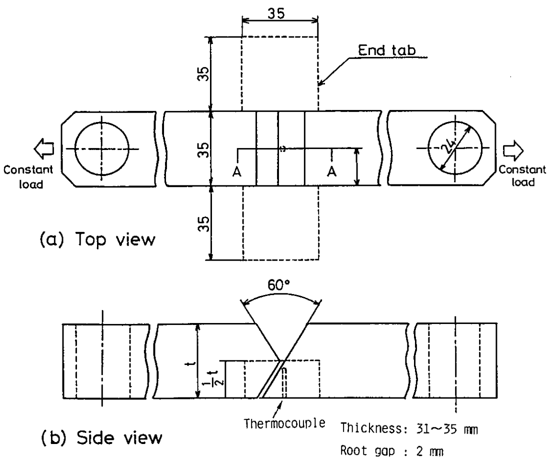


Fig. 1 Specimen configuration of the TRC test

Table 2 Diffusible hydrogen content in deposited metals

Electrode	Dia. (mm)	Diffusible hydrogen content (ml/100g) Baking temperature (°C) 400	350	150	Wetting electrode
D5016	4.0	4.1	4.6	7.9	-
D5816	4.0	5.7	7.3	11.3	18.7
D8016	4.0	3.1	3.6	4.2	6.6
DT2416	4.0	2.1	2.3	4.4	-
E(130)M	4.0	2.2	-	2.8	-

* The designations of these electrodes follow JIS (Japan Industrial Standard).
** E(130)M is experimental electrode.

Table 3 Vickers hardness in weld metal and HAZ

			Vickers hardness number (load: 10kgf)			
Base metal	Steel		HT-60	HT-80	2 1/4 Cr-1Mo	HY-130
	HAZ_{max}		360	380	360	410
Weld metal	Electrode	D5016	240	-	-	-
		D5816	270	270	300	320
		D8016	355	335	-	370
		DT2416	335	320	330	-
		E(130)M	385	355	-	370

2.2.2 *Short-term loading TRC test*

Specially programmed TRC test was done to reveal the crack initiation temperature which is the important factor in the criterion discussed later. **Figure 2** illustrates the short-term loading TRC test procedure, in which applied stress was loaded at 300°C after welding, then maintained at the constant value, and then unloaded at a temperature ranging from 250 to 100°C. After the test, about 25 pieces with 1 mm thickness were sliced from the welded zone along the transverse cross section of weld bead. These sliced pieces were etched with 5% Nital and observed in detail with light microscope in the magnification of x100 or x400 for the detection of crack initiation in HAZ or weld metal. Detailed condition of the short-term loading TRC test is shown in **Table 4**.

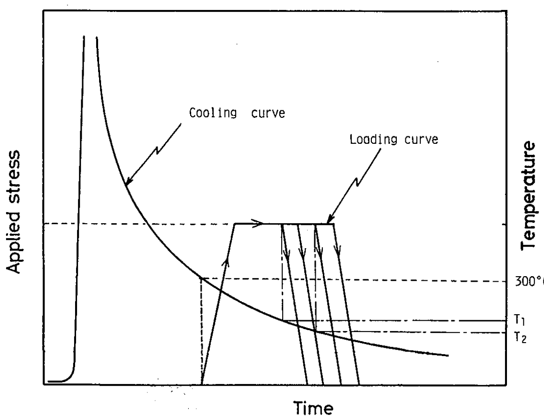


Fig. 2 Procedure of short-term loading TRC test

2.3 Fractography

Concerning the TRC specimen made by the procedure explained in 2.2, fractographic technique was used to investigate the crack initiation site. For this purpose, the fractured surface of the TRC test specimen was studied by a low magnification loupe (x10) in macrofractography and by SEM in microfractography.

3. Experimental Results

3.1 Analysis of crack initiation site based on fractographs for the ordinary TRC test specimen

It was already reported by the authors[4] that microfractographs of fractured surface of the TRC test specimen can be classified into such four regions as IG_C, CD_C, QC and D. Briefly describing these features, the IG_C region is mainly composed of intergranular (IG) fracture along grain boundary of columnar (subscript c) prior austenite in weld metal and partly of quasi-cleavage affected by hydrogen. The CDc region is mainly composed of

Table 4 Detailed condition of short-term loading TRC test

Base metal	Applied stress (kgf/mm^2)	Diffusible hydrogen content (ml/100g)	Loading temperature (°C)	Unloading temperature (°C)
HT60	55	19.5	300	250,230,200, 170,150
		5.2	300	250
HY130	40	2.7	300	170,150,130
	55	2.7	300	250,230,200,190,175,170,150, 100
		1.0	300	170,150
	80	2.7	300	250, 200, 170
		1.0	300	200, 170

quasi-cleavage (C) fracture along columnar (subscript c) crystal of prior austenite and partly of dimple (D) affected by hydrogen. Thus the IG_c and CD_c regions cracked in weld metal. The QC region is mainly composed of quasi-cleavage (QC) affected by hydrogen. The QC region cracked only in HAZ. The D region is final fractured region as dimple (D) unaffected by hydrogen.

According to the result of macroscopic fracture analysis utilizing these classification in microfractography, it was understood that there are mainly four cold cracking modes in the TRC test specimen in this study. The typical examples of these modes, namely Mode I to Mode IV are shown in **Fig. 3**, where IG_c is subdivided into $(IG_c)_p$ and $(IG_c)_i$ from the difference in location for existing region

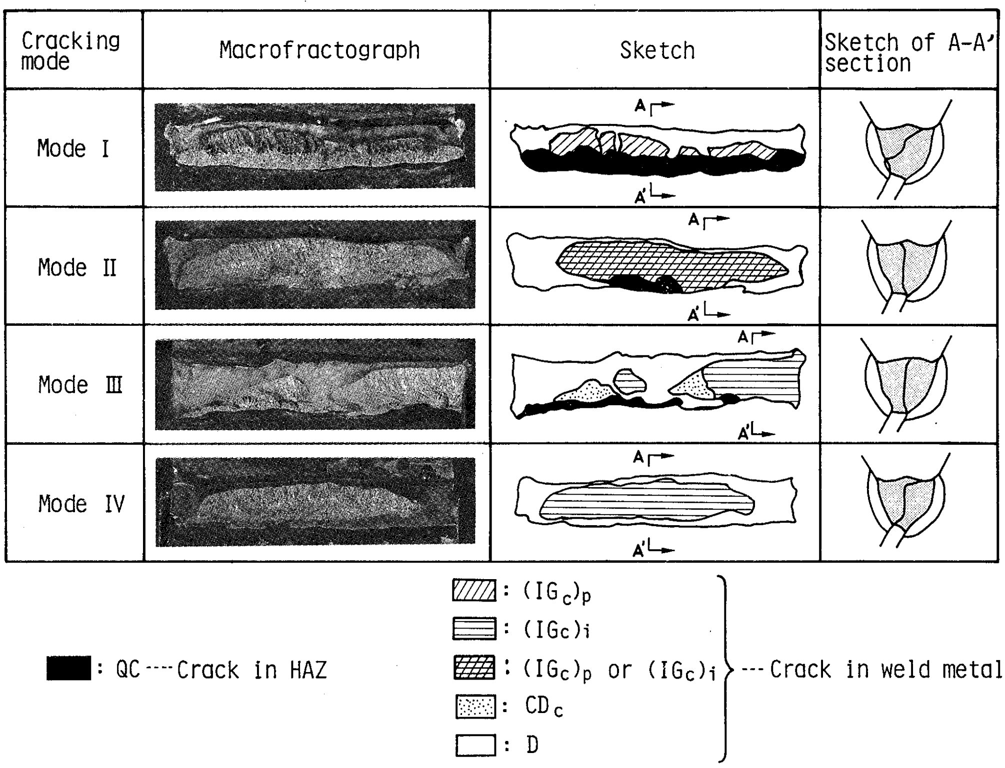
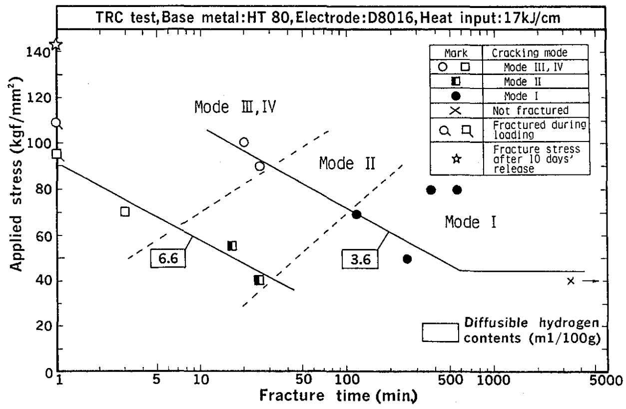


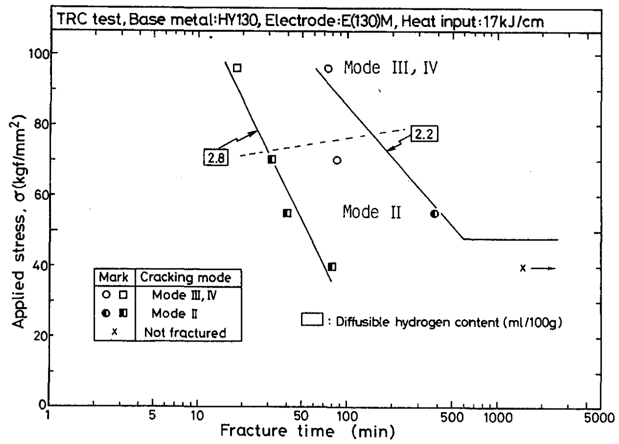
Fig. 3 Classification of fracture mode in the TRC test

of IG_c. The $(IG_c)_p$ type region is observed in only Modes I and II, and locates at the upper portion of QC. This fact and the cracking path observed in the transverse cross section suggest that the $(IG_c)_p$ region occurred during the crack propagation after crack initiation as QC in HAZ. Giving attention to the distribution of QC region, it occupies all the lowest edge of the fractured surface. Therefore, the crack initiation in Mode I surely occurred in HAZ. Now the $(IG_c)_i$ region is observed in Modes III and IV and locates independent of QC region. Especially in Mode IV, there is no QC region. Therefore, the crack initiation in Mode IV surely occurred within weld metal. In Mode III, there is a possibility that the crack initiation occurred in both HAZ and weld metal, because QC region is observed. However, judging from the much wider $(IG_c)_i$ region than QC region, it can be guessed that the crack initiation in Mode III generally occurred in weld metal. Concerning Mode II, whether the crack initiation occurred in HAZ or weld metal is very obscure in fracture analysis. It is well understood, therefore, that the tendency of crack initiation in weld metal generally increases in the direction from Mode I to IV.

The relationships between applied stress and fracture time in HT80 and HY130 in the TRC test are shown in **Fig. 4(a)** and **(b)** for two levels of initial diffusible hydrogen content. The symbol of plotted data indicates the cracking mode discussed above. Both figures of Fig. 4(a) and (b) mean that high applied stress or high diffusible hydrogen content predominantly causes the crack initiation in weld metal. In other words, crack initiation in weld metal occurs when the fracture time is short with higher stress. That is to say, the first chance for crack initiation after welding exists within the weld metal and the second exists in the HAZ after time lapse when the crack in weld metal did not occur or propagate extensively. Therefore, it is considered that the crack initiation in weld metal is related to applied stress, diffusible hydrogen content and hardness of welds, especially

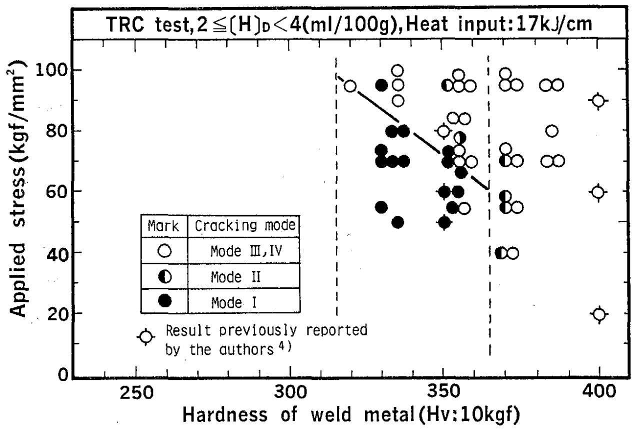


(a) HT80

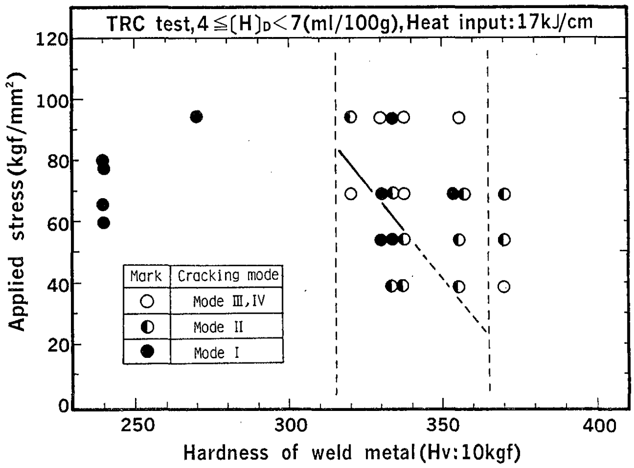


(b) HY130

Fig. 4 Relationship between applied stress and fracture time

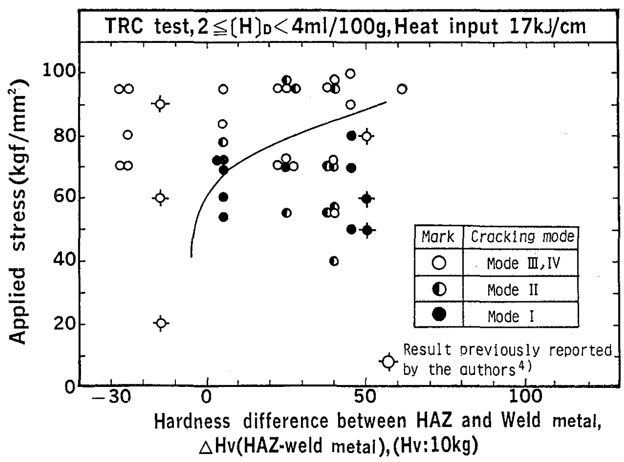


(a) $2 \leqq H_D < 4$ ml/100g

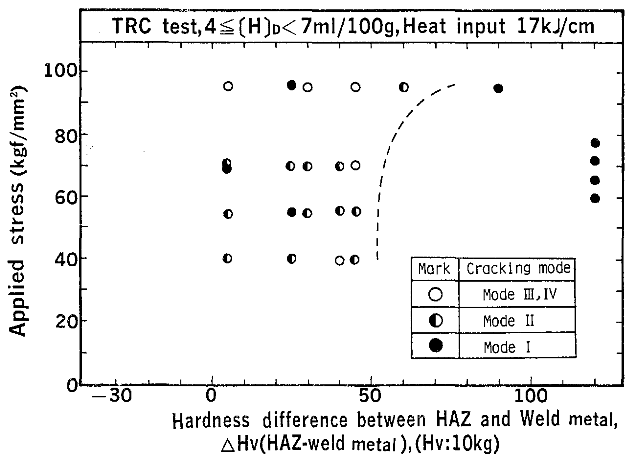


(b) $4 \leqq H_D < 7$ ml/100g

Fig. 5 Effect of diffusible hydrogen content, applied stress and hardness of weld metal on the tendency of crack initiation



(a) $2 \leqq H_D < 4$ ml/100g



(b) $4 \leqq H_D < 7$ ml/100g

Fig. 6 Effect of applied stress, diffusible hydrogen content and the hardness difference between HAZ and weld metal on crack initiation hardness of weld metal.

Figure 5(a) and **(b)** shows the relationship among the hardness of weld metal, applied stress and alternative crack initiation site for two levels of diffusible hydrogen content. Thus it is understood that high applied stress, high diffusible hydrogen content or high hardness of weld metal independently of the hardness of HAZ within the range in this experiment promote the crack initiation in weld metal. On the other hand, **Fig. 6(a)** and **(b)** shows the relationship among the hardness difference between HAZ and weld metal (ΔH_V), applied stress and alternative crack initiation site for two levels of diffusible hydrogen content. It is difficult to determine the crack initiation tendency from this figure as data are scattered. However, this figure shows another interesting result that the crack initiation in weld metal occurs even in the plus range of ΔH_V. Namely, it is indicated that the crack initiation in weld metal is able to occur even in the range of higher hardness of HAZ than that of weld metal. This fact cannot be explained by simple concept that the crack initiation occurs alternatively in HAZ or weld metal which has higher hardness between them. The reasons why the hardness of weld metal is better factor determining the crack initiation than ΔH_V in this experiment and the crack initiation in weld metal occurs even in the plus range of ΔH_V are described later.

3.2 Effect of loading temperature

Generally speaking[8),10)-12)], the diffusible hydrogen concentrates in weld metal at high temperature after welding and then diffuses to HAZ and base metal, and escapes to the atmosphere as the temperature is lowered. Therefore, it is guessed that weld metal cracking tends to occur at high temperature loading in the TRC test.

Figure 7 compares the macrofractographs and their sketches in the TRC test of HY130+E(130)M at the loading temperature of 300°C with that of 20°C in preheating of 85°C under the same hydrogen. The $(IG_C)_i$ region observed in weld metal mainly occupied the fractured surface in the loading temperature of 300°C. On the contrary, the QC region observed in HAZ occupied the lowest edge of the fractured surface in the loading temperature of 20°C. Therefore, it is easily understood that the location of crack initiation changes from weld metal to HAZ as the loading temperature is lowered. This result directly indicates that the distribution of diffusible hydrogen is one of the major factors which should be included in the criterion for the alternative crack initiation.

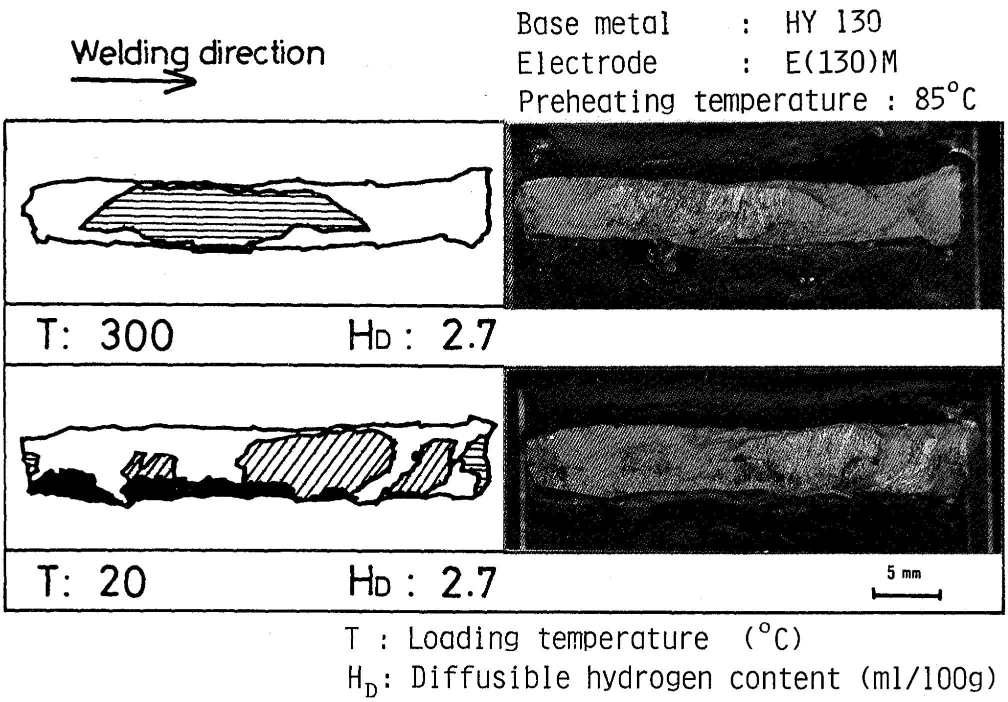


Fig. 7 Effect of loading temperature on fractured surface in the TRC test

3.3 Crack initiation temperature

The result shown in Fig. 3 to 7, now almost enable us to make the criterion, but as understood later it must be confirmed for the completion of criterion that there is upper limit temperature for crack initiation. Although this is of course widely accepted in hydrogen embrittlement, there is little data concerning the actual cold cracking in weldment.

The result for HY130 by the procedure shown in Fig. 2 is given in **Fig. 8**, which shows that the upper limit temperature for crack initiation is about 170°C independently of diffusible hydrogen content. The crack initiation temperature is slightly lowered as the applied stress decreases. The critical stress for crack initiation above about 100°C decreases with an increase in diffusible hydrogen content. By the way, it must be emphasized that all the crack initiation at 170°C occurred in weld metal.

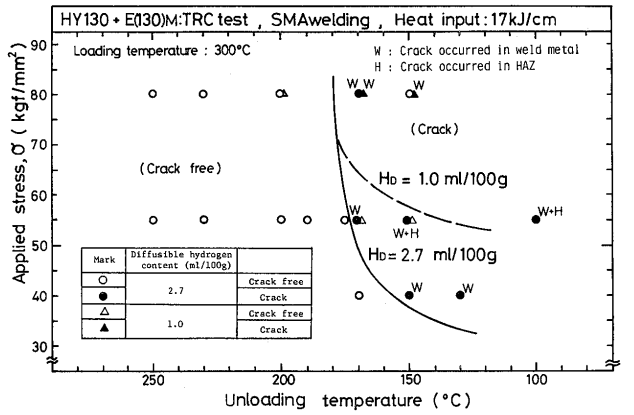


Fig. 8 Detection of the crack initiation temperature by short-term loading TRC test

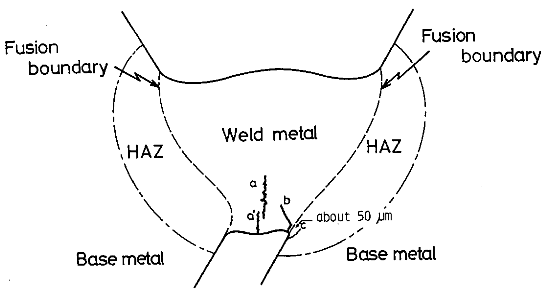


Fig. 9 Schematic illustration of cross section of weld zone showing typical location of cold cracking

On the other hand, the upper limit temperature of crack initiation in HT60 weldment was between 300 to 250°C. Interestingly the crack initiation occurred only in HAZ. This experiment gave another interesting result that the crack initiation in HAZ located at a distance of 50 μm from fusion boundary as shown schematically by *c*

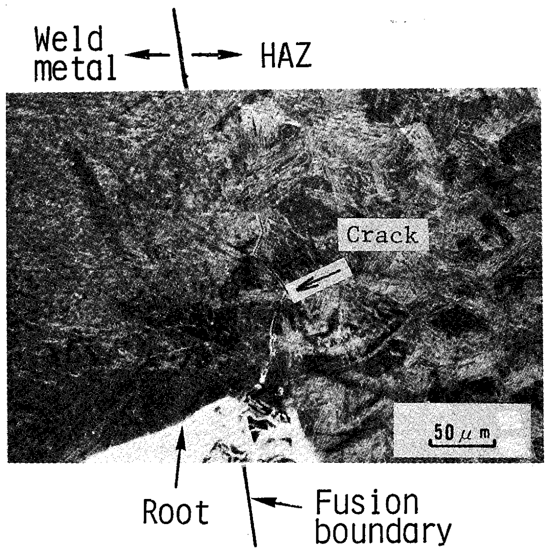


Fig. 10 Macrophotograph of cold cracking in HAZ of HY130

in **Fig. 9** and actually in **Fig. 10**. Most of the crack initiation in weld metal occurred as *a* or *a'* with rare exceptions of *b* shown in Fig. 9. The location *a* and *a'* corresponded to the center of weld metal.

4. Discussion of Criterion for Alternative Crack Initiation in HAZ or Weld Metal

Assuming the existence of both lower critical stresses for HAZ and weld metal, the result in Fig. 7 suggests that the lower critical stress in weld metal is lower than that in HAZ near the upper limit temperature discussed in Fig. 8 and that the former is higher than latter near room temperture because applied stress is constant in the TRC test. As already mentioned, factors affecting the crack initiation site are applied stress, hardness and diffusible hydrogen content. Among them, only diffusible hydrogen content is dependent upon time in the TRC test. Now, considering time dependency of lower critical stresses in HAZ and weld metal affected by the diffusible hydrogen content at each site, there may be a possibility to complete the criterion.

On the assumption that weld length is short, **Fig. 11** shows qualitatively the change in diffusible hydrogen content vs. time at the center of weld metal and HAZ which locates at a distance from fusion boundary on the basis of results in Fig. 9. The diffusible hydrogen content at the center of weld metal decreases monotonously with time due to diffusion and escape to the atmosphere. On the other hand, the diffusible hydrogen content in HAZ increases from initial zero value to maximum value and then decreases. Now it is important when the hydrogen content in HAZ reaches the maximum value. In Fig. 11 t_ℓ means the time when the temperature falls to the upper

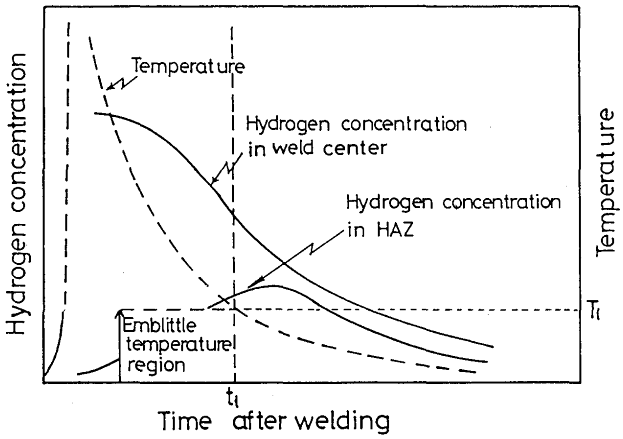


Fig. 11 Change in hydrogen concentration in weld center and HAZ after welding

limit temperature (T_ℓ) for hydrogen embrittlement. As discussed in Fig. 8, T_ℓ is about 170°C in HY130. Under the heat input of 17 kJ/cm t_ℓ was about 60 sec. According to simple calculation[13] of hydrogen content in HAZ, the time when the hydrogen content in HAZ reaches the maximum value occurs after t_ℓ. Assuming stress-induced or strain-induced diffusion[14),15] the time when the hydrogen content in HAZ reaches the maximum value occurs at the about 100 minutes after welding. Therefore it can be accepted that the time occurs after t_ℓ.

Then, as widely accepted, assume that the lower critical stress for crack initiation decreases monotonously together with hydrogen content and hardness irrespective of HAZ or weld metal. This is illustrated in **Fig. 12**, whose ordinate includes stress cocentration factor K_t for the purpose of comparison of critical stress (σ_c) between two sites of different stress concentration factor. As shown

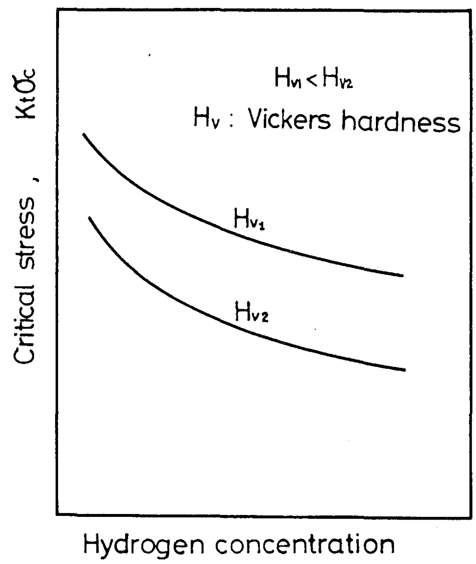


Fig. 12 Relationship between hydrogen concentration and critical stress of crack initiation

already, the crack initiation in weld metal occurs near the center of weld metal which has comparatively small stress concentration factor. On the other hand, the crack initiation in HAZ occurs near the root edge which has large stress concentration factor. In such comparison, correction of critical stress by factor K_t is considered to be most simple[16], but enough in this qualitative discussion.

Now, combination of Figs. 11 and 12 produces **Fig. 13** giving the change in critical stress in the center of weld metal (σ_{cw}) and HAZ (σ_{ch}) vs. time, which are named "Critical stress vs. time diagram" in this report. The critical stress in weld metal (σ_{cw}) monotonously increases with time lapse. On the other hand, the critical

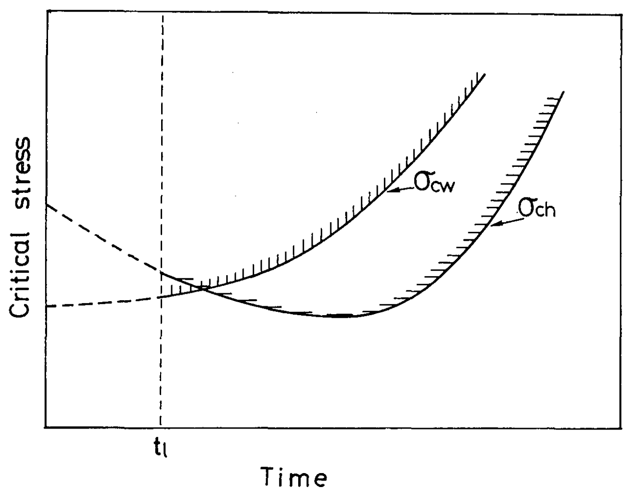
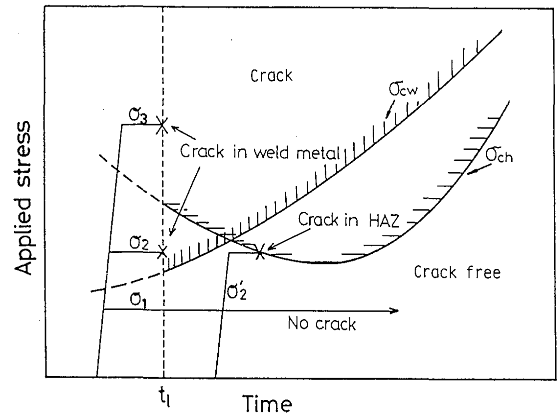


Fig. 13 Critical stress vs. time diagram

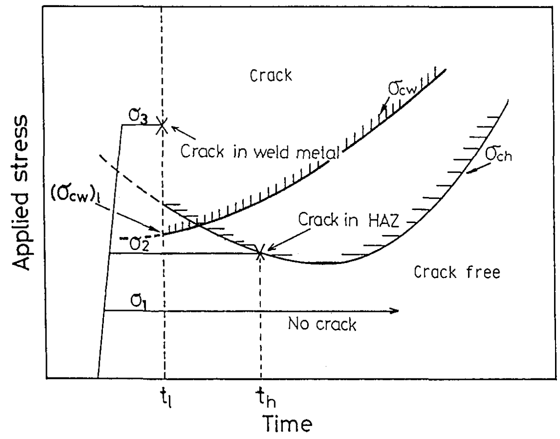
stress in HAZ (σ_{ch}) decreases to a minimum at first and then increases.

By drawing the progress of applied stress in the TRC test or restraint stress in actual case, it is possible to judge that crack initiation occurs at HAZ or weld metal as explained nextly.

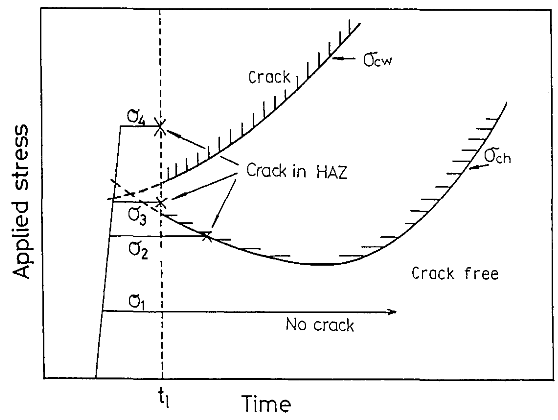
Figures 14(a), (b) and **(c)** show three types of "critical stress vs. time diagrams", where σ_1, σ_2, σ_3 and σ_4 are applied stress in the TRC test and cold cracking is able to occur at $t \geq t_\ell$. If σ_1 is applied in Fig. 14(a), cold cracking can not occur because σ_1 is lower than both σ_{cw} and σ_{ch} at any time. If σ_2 is applied, crack initiation occurs in weld metal at $t = t_\ell$ because σ_2 is higher than σ_{cw} at $t = t_\ell$. If σ_3 is applied, crack initiation occurs in weld metal at $t = t_\ell$ because (σ_3-σ_{cw}) is larger than (σ_3-σ_{ch}) at $t = t_\ell$. Therefore in Fig. 14(a) crack initiation occurs always in weld metal, which corresponds to the behavior of welded joint of HY130 steel. Interestingly if applied stress is loaded after a time lapse as like σ_2' in Fig. 14(a) crack initiation occurs in HAZ, which well



(a) Higher hardness in weld metal



(b) Medium hardness in weld metal



(c) Lower hardness in weld metal

Fig. 14 Variation of critical stress of weld metal and HAZ

corresponds to the behavior shown in Fig. 7.

Figure 14(b) shows the case where σ_{cw} is a little higher than that in Fig. 14(a) and σ_{ch} is similar to that in Fig. 14(a). If σ_1 is applied in Fig. 14(b), cold cracking cannot occur. If σ_2 is applied, crack initiation occurs in HAZ at $t = t_h$ because σ_2 is higher than σ_{ch} after t_h. If σ_3 is applied, crack initiation occurs in weld metal at $t = t_\ell$, because $(\sigma_3 - \sigma_{cw})$ is larger than $(\sigma_3 - \sigma_{ch})$ at $t = t_\ell$. Therefore in Fig. 14(b) the increase in applied stress changes the crack initiation site from HAZ to weld metal which resembles the behavior of HT80 in Fig. 4(a).

Then, Fig. 14(c) shows the case where σ_{cw} is much higher than that in Fig. 14(a). If σ_1 is applied in Fig. 14(c), crack initiation cannot occur. If σ_2, σ_3 or σ_4 is applied, crack initiation occurs in HAZ following the above discussion. Therefore in Fig. 14(c), crack initiation always occurs in HAZ, which corresponds to HT50 and HT60.

Now, defining that σ_{cw} at $t = t_\ell$ is $(\sigma_{cw})_\ell$ in Fig. 14(b), $(\sigma_{cw})_\ell$ means the applied stress at which the crack initiation site changes from HAZ to weld metal. As the hardness of weld metal increases, $(\sigma_{cw})_\ell$ of course decreases. This means that the boundary between the region of crack initiation in HAZ and the region of crack initiation in weld metal can be drawn as seen in **Fig. 15**. Moreover, if the diffusible hydrogen content becomes higher, both

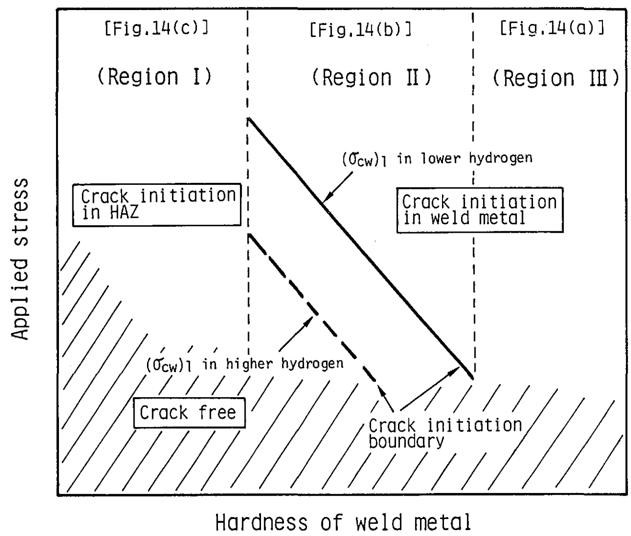


Fig. 15 Crack initiation site determined by diffusible hydrogen content, applied stress and hardness of weld metal

σ_{cw} and σ_{ch} in Fig. 14(b) is lowered and thus also $(\sigma_{cw})_\ell$ is lowered. Thus the boundary will shift to the broken line as seen in Fig. 15. Now, Fig. 15 is divided into three regions, namely Region I, II and III. The crack initiation in Region I always occurs in HAZ, which corresponds to Fig. 14(c). The crack initiation in Region III always occurs in weld metal, which corresponds to Fig. 14(a). The alternative crack initiation in HAZ or weld metal in

Region II is dependent upon the diffusible hydrogen content, hardness of weld metal when hardness of HAZ is nearly constant and applied stress, which corresponds to Fig. 14(b). Figure 15 well matches with Fig. 5 giving experimental results, and thus it is understood that the combination of applied stress (or restraint stress) and "Critical stress vs. time diagram" gives the criterion for the alternative crack initiation in HAZ or weld metal. Moreover, the reason why the hardness difference between HAZ and weld metal is not a good factor for the criterion as seen in Fig. 6 can be explained as follows: Suppose four combinations *a*, *b*, *c* and *d* of weld metal and HAZ as shown in **Table 5**. The hardness of weld metal and thus "Critical stress vs. time diagram" for weld metal in the combination *a* are the same as in the combination *b*. Similarly those in the combination *c* are the same as combination *d*. Moreover the combination *a* has the same hardness difference between HAZ and weld metal as the combination *c*, and the combination *b* has the same hardness difference as the combination *d*. **Figure 16** shows these "Critical stress vs. time diagram" and four levels of applied stress. Following the same procedure of discussion in Fig. 14, the crack initiation sites in these four combinations can be predicted, and the consequent results are shown in Fig. 16(b) where the abscissa gives hardness of weld metal, and in Fig. 16(c) where the abscissa gives the hardness difference between HAZ and weld metal. Good correlation between crack initiation site and hardness of weld metal is seen in Fig. 16(b), and no relationship between crack initiation site and hardness difference is seen in Fig. 16(c). One of the reason of no relationship in Fig. 16(c) is that the hardness difference lacks any assessment of hardness itself of weld metal or HAZ.

It must be noticed that Fig. 15 is available for the base metals whose maximum hardness in HAZ are not so widely changed as seen in this report. Extreme exception to Fig. 15 is considered as follows: Even if the hardness of weld metal locates in Region III, the crack will occur in HAZ if HAZ is so hardenable that the relation between σ_{cw} and σ_{ch} resembles Fig. 14(c).

If the distributions of diffusible hydrogen content in weld metal and HAZ are precisely calculated, and the critical stresses for crack initiation in weld metal and HAZ using the LB-TRC test[17] and the Implant test are experimentally obtained, the "critical stress vs. time diagram" is quantitatively drawn and the alternative crack initiation

Table 5 Examples of four combinations of HAZ and weld metal

Combination of HAZ and weld metal	Hardness		Hardness difference $\Delta H (\equiv H_h - H_w)$	Critical stress vs. time diagram	
	Weld metal	HAZ		Weld metal	HAZ
a	H_{w1}	H_{h1}	ΔH_S	σ_{cw1}	σ_{ch1}
b	H_{w1}	H_{h2}	ΔH_L	σ_{cw1}	σ_{ch2}
c	H_{w2}	H_{h3}	ΔH_S	σ_{cw2}	σ_{ch3}
d	H_{w2}	H_{h4}	ΔH_L	σ_{cw2}	σ_{ch4}

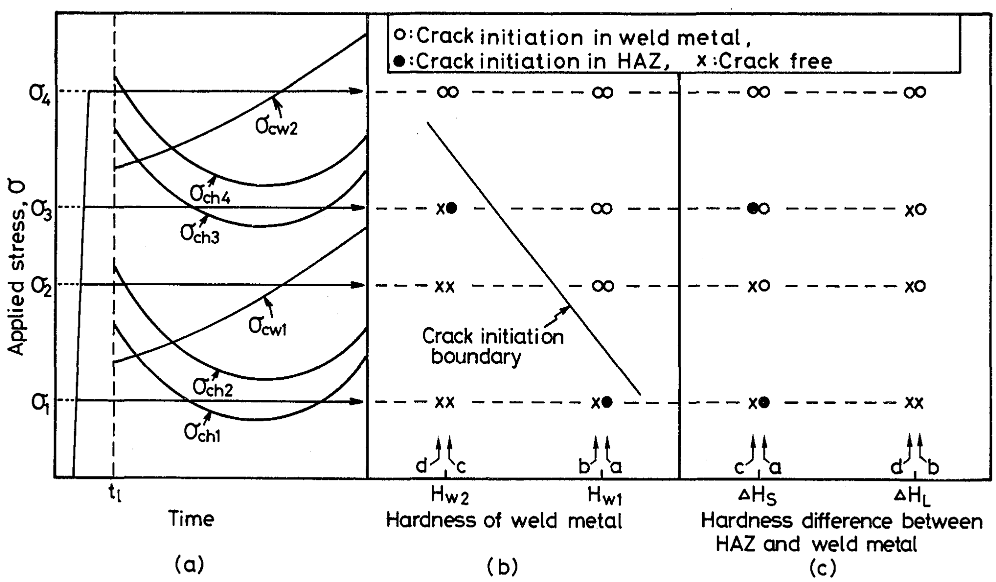


Fig. 16 Effect of hardness of weld metal or ΔH_V on crack initiation site

can be predicted. Reference [13] gives simple trial by calculation about this problem. By the way, according to the discussion in Fig. 14, crack initiation time in weld metal is generally faster than in HAZ. Perhaps it is reasonable to consider that the former case shows the faster fracture time than the latter. This phenomenon is observed in Fig. 4. and reference [7]. Therefore "Critical stress vs. time diagram" is also available in this point.

5. Conclusion

In order to reveal the criterion under which cold cracking in root pass welding occurs alternatively in HAZ or weld metal, the effect of applied stress, diffusible hydrogen content, hardness of HAZ and weld metal on the crack initiation site were studied utilizing the TRC test for HT60, HT80, HY130 and 2¼Cr-1Mo steels. In this study the maximum hardnesses of HAZ were ranged from 360 to 410 and the hardnesses of weld metal were ranged from 240 to 385. Then, "Critical stress vs. time diagram" was proposed as the criterion. Main conclusions obtained are as follows;

(1) Generally high applied stress, high diffusible hydrogen content or high hardness of weld metal causes the crack initiation in weld metal.

(2) Usual loading at 150°C in the TRC test for HY130 causes the crack initiation in weld metal, but loading at room temperature caused the crack initiation in HAZ. On the other hand, the loading for HT60 even at 300°C didn't cause the crack initiation in weld metal but did in HAZ.

(3) In the TRC test specimen where the crack initiation occurs in weld metal, the fracture time is relatively short.

(4) All the phenomena in conclusions (1) to (3) can be well explained by combining the progress of applied stress and "Critical stress vs. time diagram", which represent the change in critical stresses in weld metal and HAZ vs. time lapse. Therefore, critical stress vs. time diagram gives the criterion of alternative crack initiation in HAZ or weld metal.

(5) It is confirmed that there is definite upper limit temperature of cold cracking. The upper limit temperature was about 170°C in the weldment of HY130 and about 300 to 250°C in the weldment of HT60.

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